Recent results on $\psi(2s)$ and χ_c from BES

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Representing The BES Collaboration

1 Introduction

The BES collaboration has become well known due to it's successful precision measurement on τ lepton mass[1], while it's succesive works on $J/\psi, \psi(2s), D_s$ make the further contribution for the τ charm physics[2]. By now, BES has collected 9 million J/ψ, 3.6 million $\psi(2s)$ events and 22.3 pb^{-1} τ, D_s, D data sample. Vevy soon BES will complete it's upgrade task, therefore it will significantly improve the power of particle ID and secondary vertex finding, the precision of the momentum measurement, and enlarge the solid angle coverage. The more and better physics results can be expected.

As BES has the largest $\psi(2s)$ data sample in the world, we are able to investigate many channels of $\psi(2s)$ decays and to extend our study to other chamonium states, such as χ_c, η_c etc.. In this talk I will concentrate on the results which are newely measured or precision improved by BES Collaboration.

2 BES detector

The detector BES has been described in reference [3]. The principal sub-detectors of BES are central drift chamber (CDC), main drift chamber (MDC), barrel and endcap shower counters (BSC,ESC), barrel and endcap time of flight counters (BTOF,ETOF), magnet (with 0.4 T magnetic field), muon counters (MUC) and luminosity monitor (LUM). Here we summarize only some elements. The CDC consisting of four layers of sense wires is used for trigger purposes. Charged track reconstruction is performed by means of the cylindrical MDC which covers 85% of the 4π solid angle. Together with a 0.4 T magnetic field, the MDC provides a momentum resolution of $\sigma_p/p = 0.017\sqrt{1+p^2}$, p in GeV/c. Measurements of dE/dx with resolution 8.5% allow particle identification. The BTOF consists of 48 scintillation counters, which cover 76% of 4π solid angle and provide a time resolution of 330 ps for Bhabha tracks. Between the BTOF and the coil of the solenoid is the BSC, which consists of 24 layers of alternating 0.5 radiation-length lead sheets and self-quenching streamer mode tubes. The solid angle coverage is about 80% of 4π and the energy resolution σ_E/E is $0.22/\sqrt{E(GeV)}$. Finally, a three-layer iron flux return instrumented for muon identification yields spatial resolution $\sigma_z = 5cm$,$\sigma_{r\varphi} = 3cm$ over 65% of 4π for muons with momentum greater than 550 MeV/c.

3 The measurements of $\psi(2s)$ decays

3.1 Branching fraction of $\psi(2s) \to \tau^+\tau^-$

Using 1.27 million produced $\psi(2s)$ events, the branching fraction for $\psi(2s) \to \tau^+\tau^-$ decay has been measured with the result of

$$B(\psi(2s) \to \tau^+\tau^-) = (3.5 \pm 0.5 \pm 0.6) \times 10^{-3}$$

Assuming $e-\mu-\tau$ universality and considering lepton mass, following relation holds:

$$B_{ee} = B_{\mu\mu} = B_{\tau\tau}/0.3885.$$

Our measurement for $B_{\tau\tau}$, together with existing data of $B(\psi(2s) \to e^+e^-) = (8.8 \pm 1.3) \times 10^{-3}$ and $B(\psi(2s) \to \mu^+\mu^-) = (7.7 \pm 1.7) \times 10^{-3}$, satisfies the prediction of $e-\mu-\tau$ universality hypothesis.

3.2 The hadronic decays of $\psi(2s)$

3.2.1 Branching fractions of $\psi(2s)$ decays to VP and VT mesons

There has been a long-standing puzzle in J/ψ and $\psi(2s)$ decays into vector plus pseudoscalar exclusive final states. As early as 1983, The Mark II Collaboration first found two final states,$\rho\pi$ and $K^{*\pm}K^{\mp}$, unobservable in $\psi(2s)$ decays, with a data sample of 1.02×10^6 produced $\psi(2s)$,while both of them have a large branching fraction in J/ψ decays[4]. It has been noted that the ratios of branching fractions of $\psi(2s)$ and J/ψ to these two final states[5]: $Q_{\rho\pi} < 0.0063$, $Q_{K^*\overline{K}} < 0.011$, badly violated the expectation of PQCD that, for any final hadronic state h, the ratio Q_h scales as the ratio of the 3 gluon widths which are proportional to the leptonic widths devided by the full widths:

$$Q_h \equiv \frac{B(\psi(2s) \to h)}{B(J/\psi \to h)} = \frac{B(\psi(2s) \to ggg)}{B(J/\psi \to ggg)} = \frac{B(\psi(2s) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.7 \pm 2.3)\%$$

where the updated values of leptonic branching fractions from Particle Data Table [5] are used. More recently, the Crystal Ball experiment observed another two decays of the $\psi(2s)$ into VP final states, $\gamma\eta$ and $\gamma\eta\prime$, where the vector is a photon, that are anomalously suppressed[6]. However, the Crystal Ball results have never been formally published, and the Mark II measurements of $\psi(2s)$ decays have not been renewed till 1995 Beijing Lepton Photon Conference.

With 1.27 million produced $\psi(2s)$ events, BES collaboration reported on the 1995 Lepton-Photon Conference the preliminary results of the branching fractions of the $\psi(2s)$ decays into a vector and a pseudoscalar mesons, $\rho\pi, K^{*\pm}K^{\mp}$, $K^{*0}\overline{K^0}$. BES also reported the first measurement on the branching fractions of $\psi(2s)$ decay into vector-tensor final states, ωf_2 and ρa_2. It is found that all these decays are substantially suppressed in the $\psi(2s)$ decays compared to the PQCD prediction relative to the corresponding J/ψ decays.

Recently BES has systematically studied the $\psi(2s)$ hadronic decays to VP, VT and AP meson final states with 3.6 million produced $\psi(2s)$ events collected from 1993 to 1995. The number of $\psi(2s)$ events, $N_{\psi'}$, are determined by three independent ways. (1)Direct determination. (2) $N_{\psi'}$ is inferred from J/ψ production in $\psi(2s) \to \pi^+\pi^-J/\psi$ decay where the J/ψ production is inferred in the recoil from the $\pi^+\pi^-$ system. (3) $N_{\psi'}$ is inferred from J/ψ production in $\psi(2s) \to \pi^+\pi^-J/\psi$ decay where the J/ψ is observed from its direct decay into $\mu^+\mu^-$ final states. These three methods give a same results within error of 4%.

With this high statistics study, BES obtained intresting results on VP and VT final states of $\psi(2s)$ decays in Table 1. Following conclusions can be extracted:

1. For the $\rho\pi$ and $K^{*\pm}K^{\mp}$ decay modes, BES set a new upper limits at 90% confidence level for the branching fractions of

$$B(\psi(2s) \to \rho\pi) < 2.9 \times 10^{-5},$$
$$B(\psi(2s) \to K^{*\pm}K^{\mp}) < 3.2 \times 10^{-5}.$$

These values are significantly lower than the corresponding upper limits set by Mark II group[4]. Using the PDG values of branching fractions of J/ψ decays to corresponding final states, BES set the limits on the ratios of branching fractions:

$$Q_{\rho\pi} < 0.0023, \quad Q_{K^{*\pm}K^{\mp}} < 0.0064.$$

These are more than a factor of 60 and 20 below the PQCD predictions, respectively. Therefore, BES has confirmed and improved the previous observation of VP suppression of $\psi(2s)$ decays.

2. BES made the first measurement of the $\psi(2s)$ decay to $K^{*0}\overline{K}^0$ final state (VP mode). The branching fraction of this channel is

$$B(\psi(2s) \to K^{*0}\overline{K}^0) = (8.4 \pm 2.9) \times 10^{-5}.$$

Using the PDG value of branching fraction of J/ψ decay yields the ratio of branching fractions

$$Q_{K^{*0}\overline{K}^0} = 0.020 \pm 0.007.$$

3. There have been a number of theoretical attempts to explain the VP suppression puzzle[7,8]. However, it seems none of them can explain the existing data.

4. The $\psi(2s)$ decays into $2(\pi^+\pi^-)\pi^0$ and $\pi^+\pi^-K^+K^-$ final states have been studied from fully reconstructed events. Three vector-tensor combinations,ωf_2, ρa_2 and $K^{*0}\overline{K}_2^{*0}$, are measured in $\psi(2s)$ decays for the first time. The branching fractions are

$$\begin{aligned} B(\psi(2s) \to \rho a_2) &= (31 \pm 19) \times 10^{-5}, \\ B(\psi(2s) \to \omega f_2) &< 15 \times 10^{-5}, \\ B(\psi(2s) \to K^{*0}\overline{K}_2^{*0}) &< 18 \times 10^{-5}. \end{aligned}$$

Using the PDG values of branching fractions of J/ψ decays to corresponding final states, we obtained the ratios of branching fractios:

$$Q_{\rho a_2} = 0.028 \pm 0.017, \quad Q_{\omega f_2} < 0.035, \quad Q_{K^{*0}\overline{K}_2^{*0}} < 0.028,$$

much lower than the prediction of PQCD. It changes the long-time adopted picture that the anomaly in charmonium hadronic decays is only seen in vector-pseudoscalar final states. Now the puzzle extends to the VT decay!

5. The discovery of VT anomaly is theoretically even more puzzling. The vector- pseudoscalar decays,$\rho\pi$,$K^{*\pm}K^{\mp}$ and $K^{*0}\overline{K}^0$, are stronly suppressed and they are not allowed by the pertubative QCD theorem that total hadron helicity is conserved (HHC) in high-momentum-transfer exclusive processes[8]. However, a recent analysis [9] has shown that the vector-tensor decays,ωf_2, ρa_2 and $K^{*0}\overline{K}_2^{*0}$, are allowed by the HHC theorem. Hence their suppression poses new challenges to the theory.

Table 1. Experimental Ratios of VP and VT modes

	Decay Mode	B($\psi(2s)$) (10^{-5})	B(J/ψ) (10^{-3})	Q (%)
VP	$\rho\pi$	< 2.9	12.8 ± 1.0	< 0.23
	$K^{*\pm}K^{\mp}$	< 3.2	5.0 ± 0.4	< 0.64
	$K^{*0}\overline{K}^0$	8.4 ± 2.9	4.2 ± 0.4	2.0 ± 0.7
VT	ωf_2	< 15	4.3 ± 0.6	< 3.5
	ρa_2	31 ± 19	10.9 ± 2.2	2.8 ± 1.7
	$K^{*0}\overline{K}_2^{*0}$	< 18	6.7 ± 2.6	< 2.8

note : (1) Upper limits are at 90% confidence level.
(2) J/ψ data are from PDG
(3) $\psi(2s)$ data are from BES measurement

3.2.2 Branching fractions of $\psi(2s)$ decays to octet-baryon pairs

In the context of flavor SU(3), a pure $c\overline{c}$ state is a flavor singlet and, in the limit of SU(3) flavor symmetry, the phase-space- corrected reduced branching fractions to any baryon octet pair, $| M_i |^2$,

$$| M_i |^2 = \frac{B(\psi(2s) \to B_i\overline{B_i})}{\pi p^*/\sqrt{s}}$$

(p^* is the momentum of the baryon in the $\psi(2s)$ rest frame), should be the same for every octet baryon,B_i. Deviations from this rule would indicate a non- $c\overline{c}$ component of the charmonium wave function. The reduced branching fractions for $J/\psi \to B_8\overline{B}_8$ decays are shown in Table 2. The SU(3) relation works reasonably well, although there may be some preference for the $p\overline{p}$ mode.

This relation has not been tested for the $\psi(2s)$, where the only relevant branching fraction that has been measured is $\psi(2s) \to p\overline{p}$, and that with rather poor precision[10].

Here we report preliminary results of measurements of the branching fractions for $\psi(2s) \to B_i\overline{B}_i$, where $B_i = p, \Lambda, \Sigma^0, \Xi^-, \Delta^{++}, \Sigma^{*-}, \Xi^{*0}$ and Ω^-, using a sample of 3.6 million produced $\psi(2s)$ events. The measured branching fractions are listed on Table 3, together with their ratios of branching fractions, Using the PDG values of branching fractions of J/ψ decays to corresponding final states. It seems, They basicaly agree with the PQCD's expectation. The reduced branching fractions derived from our measurements have been included in Table 2. The results show a trend to smaller values for the higher masses, showing some deviation from expectations based on flavor SU(3) symmetry. Higher precision measurements both for the J/ψ and $\psi(2s)$ would clarify this problem.

Table 2. Reduced branching fractions $| M_i |^2$ for $J/\psi, \psi(2s) \to B_i\overline{B}_i$ (10^{-4})

	$p\overline{p}$	$\Lambda\overline{\Lambda}$	$\Sigma^0\overline{\Sigma}^0$	$\Delta^{++}\overline{\Delta}^{--}$	$\Xi^-\overline{\Xi}^-$	$\Sigma^{*-}\overline{\Sigma}^{*+}$
$| M_i |^2_{J/\psi}$ (10^{-4})	17.1 ± 0.8	12.4 ± 1.3	12.6 ± 1.7		10.9 ± 2.4	
$| M_i |^2_{\psi'}$ (10^{-4})	2.02 ± 0.29	1.69 ± 0.28	0.78 ± 0.40	0.76 ± 0.22	0.76 ± 0.27	0.54 ± 0.26

Table 3. Experimental Ratios of $B_8\overline{B}_8$ modes

Decay Mode	B($\psi(2s)$) (10^{-5})	B(J/ψ) (10^{-3})	Q (%)
$p\overline{p}$	27.3 ± 3.9	2.14 ± 0.10	12.8 ± 1.9
$\Lambda\overline{\Lambda}$	21.1 ± 3.5	1.35 ± 0.14	15.6 ± 3.1
$\Sigma^0\overline{\Sigma}^0$	9.4 ± 4.8	1.3 ± 0.2	7.2 ± 3.9
$\Delta^{++}\overline{\Delta}^{--}$	8.9 ± 2.6	1.10 ± 0.29	8.1 ± 3.2
$Xi^-\overline{\Xi}^-$	8.3 ± 3.0	0.9 ± 0.2	9.2 ± 3.9
$\Sigma^{*-}\overline{\Sigma}^{*+}$	5.6 ± 2.7	1.03 ± 0.13	5.4 ± 2.7
$\Xi^{*0}\overline{\Xi}^{*0}$	< 7.5		
$\Omega^-\overline{\Omega}^+$	< 8.3		

4 The measurements of χ_{c0} decay width

The charmonium p-wave triplet states χ_{cJ} (J=0,1,2) were found soon after the J/ψ and $\psi(2s)$ discovery in 1970's, but most of their decay parameters were measured before 1980's. Recently E760 experiment [11] at Fermilab measured the total widths and $p\overline{p}$ partial widths for χ_{c1} and χ_{c2}, but for χ_{c0} the scan has not been done yet. The measured value of χ_{c0} decay width, $\Gamma_{\chi c0} = 13.5 \pm 3.3 \pm 4.2 MeV$, are from Crystal Ball experiment [12], which is the weighted average of two values : 13-21 Mev from $\psi(2s) \to \gamma X$ study and $8.8 \pm 1.3 \pm 1.5 MeV$ from $\psi(2s) \to \gamma\pi^0\pi^0$.

Using 3.6 million produced $\psi(2s)$ events we select $\gamma\pi^+\pi^-$ and γK^+K^- events by proper selection criteria, and then using kinematic fit to reduce backgrounds. The obtained $\pi^+\pi^-$ and K^+K^- invariant mass spectra are shown in Fig. 1, which shows two clear peaks corresponding to χ_{c0} and χ_{c2}, respectively. Parity conservation law forbids χ_{c1} and $\eta_c(2s)$ production in the studied final states, therefore, there is no distortion of the χ_{c0} and χ_{c2} spectra due to contaminations from other resonances. The mass resolution of χ_{c2} obtained from our Monte Carlo simulation is calibrated by fitting our measured peak with known accurate χ_{c2} width by E760 experiment. Hence we can infer the reliable mass resolution at χ_{c0} mass region.

However, there exist cross contamination in the invariant mass distribution between $\pi^+\pi^-$ and K^+K^- channels. Theory and experiments have shown[13] that χ_{cJ} is generated via pure E1 transition of $\psi(2s)$ and $\chi_{cJ} \to 0^-0^-$ meson pairs has only one independent helicity amplitude. The Monte Carlo simulation was done based on the generator with the mechanism stated above to determine the detection efficiencies for both channels and the cross contamination probabilities betweem them. After this correction, fitting the invariant mass spectra with the fixed χ_{c2} width 2.00 MeV (from PDG) yields following results:

$$\Gamma_{\chi_{c0}} = 15.0 \pm^{3.3}_{2.8} MeV,$$

where the error includes the statistical and the systematic. This result is in agreement with the world average value, but with higher precision. The ratio of our measured $\Gamma_{\chi_{c0}}$ to $\Gamma_{\chi_{c2}}$ (PDG) is $7.5 \pm^{1.8}_{1.6}$, which agrees with W.Kwong's theoretical prediction[14], while it has large discrepancy with the calculation by G.T.Bodwin[15].

We have also obtained the partial widths of χ_{c0},χ_{c2} decays to $\pi^+\pi^-$,K^+K^- and $p\overline{p}$ listed in Table 4. it can be seen that the BES measurements are more precise than PDG values. For partial widths of $\chi_{c0} \to \pi^+\pi^-, K^+K^-$, BES measurements deviate from PDG values significantly, while for other partial widths they coinside in one standard deviation. From the branching fractions listed in Table 4, we obtained following ratios:

$$\begin{aligned}\frac{B(\chi_{c0}\to\pi^+\pi^-)}{B(\chi_{c0}\to K^+K^-)} &= 1.24\pm0.13,\\ \frac{B(\chi_{c2}\to\pi^+\pi^-)}{B(\chi_{c2}\to K^+K^-)} &= 2.95\pm1.18,\\ \frac{B(\chi_{c0}\to\pi^+\pi^-)}{B(\chi_{c2}\to\pi^+\pi^-)} &= 2.81\pm0.63,\\ \frac{B(\chi_{c0}\to K^+K^-)}{B(\chi_{c2}\to K^+K^-)} &= 6.6\pm2.7.\end{aligned}$$

Do these ratios mean that there exist asymmetry in the decays of $\chi_{c0},\chi_{c2}\to\pi^+\pi^-,K^+K^-$? This is an open question and needs more precise data.

Table 4. Partial widths for χ_{c0} and χ_{c2} decays to $\pi^+\pi^-$, K^+K^- and $p\overline{p}$ (10^{-4})

		$\pi^+\pi^-$	K^+K^-	$p\overline{p}$
χ_{c0}	BES	42.7 ± 6.4	34.4 ± 5.1	1.45 ± 0.50
	PDG	75 ± 21	71 ± 24	<9.0
χ_{c2}	BES	15.2 ± 3.4	5.2 ± 2.1	0.96 ± 0.54
	PDG	19 ± 10	15 ± 11	1.00 ± 0.10

5 Summary

With the largest $\psi(2s)$ events sample in the world, BES is able to study its decays more precisely and to extend the investigation to other charmonium states, such as χ_c, η_c, etc.. Significant improvements have been reached in many decay channels by BES measurements.

1. The branching fraction of $\psi(2s)\to\tau^+\tau^-$ has been determined for the first time to be $(3.5\pm0.5\pm0.6)\times10^{-3}$. This value conserves the $e-\mu-\tau$ universality.

2. Severe suppression is observed in $\psi(2s)$ decays into a vector and a pseudoscalar mesons, $\rho\pi$, $K^{*\pm}\overline{K}^{\mp}$, and $K^{*0}\overline{K}^0$.

3. Sgnificant suppression is seen in $\psi(2s)$ decays into vector-tensor final states, ωf_2, ρa_2 and $K^{*0}\overline{K}^{*0}_2$.

4. existing theoretical models can not explain observed suppression.

5. The total decay width for χ_0 and the patial decay widths of $\pi^+\pi^-$, K^+K^- and $p\overline{p}$ for χ_0 and χ_2 have been measured with improved accuracies. The open question is if there exists asymmetry in the decays of $\chi_{c0},\chi_{c2}\to\pi^+\pi^-,K^+K^-$.

It seems that, the present situation of charmonium physics is still very mystery. The big challenge both in theoretical and experimental aspects are put in front of physicists on the way going to real understanding for the nature.

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